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Briefing charts presented at ILASS Americas 27th Annual Conference on Liquid Atomization and Spray Systems in Raleigh, NC; 17 May 2015.

**14. ABSTRACT**
Shear coaxial injectors are so named because they rely on the shear between an outer low-density, high-velocity annulus and a high-density, low-velocity inner jet to atomize and mix a liquid and a gas. These sprays have an intact core near the injector and the high amount of light scattering its corrugated surface produces creates large optical densities. These high optical densities, in turn, make interrogation of the spray field in the intact core difficult. In combustion applications, such as rockets, this region is also the area of flame holding, and so is of primary importance in predicting combustion behavior. To overcome the problems of multiple scattering, the near-injector region was studied using x-ray radiography at Argonne National Laboratory's Advanced Photon Source. These results clearly show regions which correspond to changes in atomization behavior and can be used to quantify "core length" and understand more clearly what this term means. Three methods are explored to measure core length from x-ray radiography data and are compared to two-phase core length measurements from the literature. The core length nondimensionalized by the inner jet diameter was found to scale with the momentum flux to the -0.66 power.

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# Core Length and Spray Width Measurements in Shear Coaxial Injectors from X-ray Radiography Measurements

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# Motivation

- **As new diagnostic methods are applied to unit physic type problems it is important to understand how the new results compare with the existing knowledge of the flow field**
- **X-ray radiography has developed over the past decade from a proof-of-concept measurement to a developed diagnostic technique for the quantitative measurement of sprays**
  - The high flux monochromatic X-ray beam from a synchrotron X-ray source allows for time-resolved measurements with minimal corrections
  - Main interaction is absorption, not scattering
  - Mass based: insensitive to liquid-gas interfaces
  - Used to study diesel, swirl, gas-centered swirl-coaxial, impingers, and aerated liquid jet injectors
  - Has primarily been used to make measurements that were difficult to make any other way

- **Presentation focuses on using quantitative projected density measurements of shear coaxial jets to define atomization regions and quantify "core lengths"**
  - Focus on core lengths allows comparison with literature data

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# Shear Coaxial Injectors

- **Shear coaxial jets can be found in a number of combustion devices**
  - Turbofan engine exhaust, air blast furnaces, and liquid rocket engines
- **Substantial fundamental research exists on single phase coaxial jets**
  - Quantitative mass distributions and velocity fields measured using PLIF and velocimetry
  - Includes the case where both fluids are supercritical
  - Common in modern boost-class liquid rocket engines
- **Current focus is on two-phase coaxial jets for rocket engine applications**
  - Common in upper-stage engines and during throttled conditions, startup and shutdown transients of boost-class engines
  - Previous scaling efforts have been largely based on imaging of the liquid core
- **Gaseous high speed outer jet (fuel) is used to fragment a dense liquid core (oxidizer)**
  - Fuel is typically $H_2$ or $CH_4$ and oxidizer is LOX
  - For the current study liquid $H_2O$ and gaseous $N_2$ are used as surrogates for oxidizer and fuel respectively

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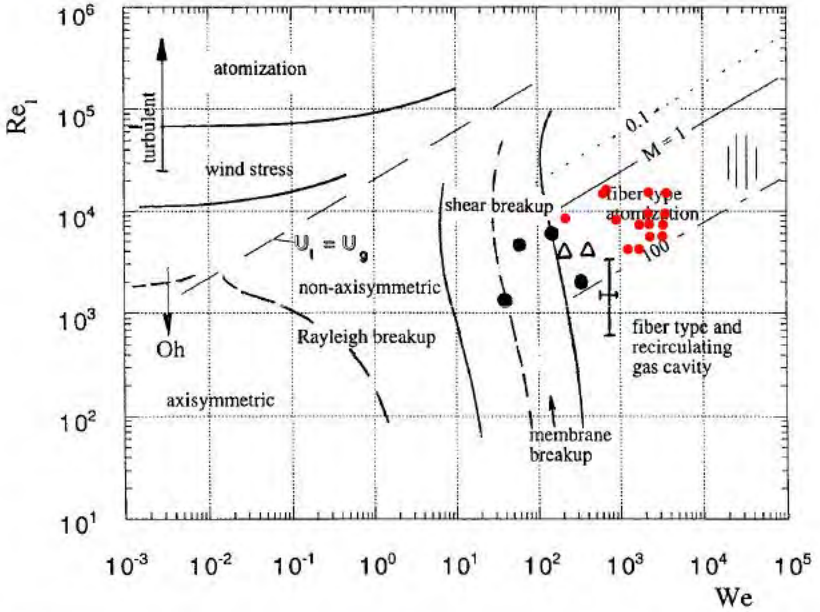
# Controlling Parameters and Regimes

- **Previous studies indicate two-phase coaxial jet atomization is controlled by 6 nondimensional parameters**
  - Liquid and gas Reynolds number (*Re*), Ohnesorge number (*Oh*), Weber number (*We*), momentum flux ratio (*J*), and mass flux ratio (*m*)
  - *J* defined gas to liquid and *m* liquid to gas
- **Test conditions all in the fiber type atomization regime (red points)**
- **Since test conditions are in the fiber type regime *J* and *m* are the controlling parameters**
  - *J* controls primary atomization
  - *m* effects far field momentum transfer and degree of interaction between shear layers
  - Area ratio effects are accounted for in *m*




Regime Diagram: *Lasheras, J.C., and Hopfinger, E.J. Annual Review of Fluid Mechanics 32:275-308 (2000).*

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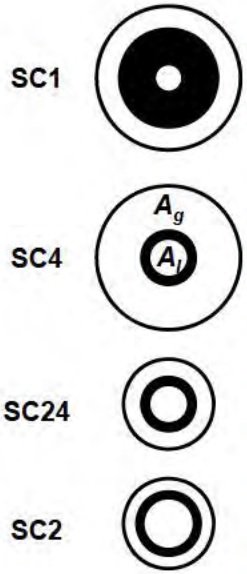
# Test Matrix

- **Test conditions based on 5 nominal *J* conditions (0.5, 2, 5, 10, & 15)**
  - Gas velocities ($U_g$): 81-229 m/s, liquid velocities ($U_l$): 2.0-6.0 m/s
  - Weber #: 211-2260, Reynolds #: Gas: 8,900-52,000 & Liquid: 4,200-16,500
- **SC4 and SC24 have the same inner jet geometry and use similar velocities at each *J* conditions, therefore, the 3.4 factor in *m* between SC4 and SC24 is due solely to the difference in area ratio**




| Condition | Φ | $U_g$ (m/s) | $U_l$ (m/s) | $\dot{m}_g$ (g/s) | $\dot{m}_l$ (g/s) | m | We | $Re_g$ | $Re_l$ |
|---|---|---|---|---|---|---|---|---|---|
| SC1-0.5 | 0.46 | 81 | 4.0 | 4.16 | 13.6 | 3.27 | 211 | 8,920 | 8,370 |
| SC1-2 | 1.9 | 162 | 4.0 | 8.53 | 13.6 | 1.59 | 872 | 18,800 | 8,260 |
| SC1-5 | 4.8 | 220 | 3.5 | 12.0 | 11.8 | 0.98 | 1667 | 27,600 | 7,290 |
| SC1-10 | 9.6 | 182 | 2.0 | 9.62 | 6.79 | 0.71 | 1100 | 21,400 | 4,210 |
| SC1-15 | 14 | 219 | 2.0 | 12.0 | 6.79 | 0.57 | 1651 | 27,300 | 4,240 |
| SC4-0.5 | 0.49 | 125 | 6.0 | 9.85 | 36.7 | 3.72 | 673 | 25,800 | 15,700 |
| SC4-2 | 2.0 | 229 | 5.5 | 18.4 | 33.6 | 1.82 | 2310 | 50,600 | 14,500 |
| SC4-5 | 4.8 | 224 | 3.5 | 18.5 | 21.4 | 1.16 | 2260 | 51,800 | 9,150 |
| SC4-10 | 9.1 | 219 | 2.5 | 18.4 | 15.4 | 0.84 | 2200 | 52,000 | 7,050 |
| SC4-15 | 15 | 224 | 2.0 | 18.4 | 12.0 | 0.65 | 2250 | 51,400 | 5,590 |
| SC24-0.5 | 0.46 | 120 | 6.0 | 2.88 | 36.7 | 12.7 | 635 | 10,400 | 16,500 |
| SC24-2 | 1.8 | 212 | 5.6 | 5.40 | 34.3 | 6.34 | 2104 | 20,100 | 16,000 |
| SC24-5 | 4.6 | 210 | 3.5 | 5.51 | 21.4 | 3.88 | 2120 | 21,000 | 9,340 |
| SC24-10 | 8.7 | 211 | 2.5 | 5.44 | 15.4 | 2.83 | 2110 | 20,400 | 7,310 |
| SC24-15 | 15 | 213 | 2.0 | 5.48 | 11.9 | 2.18 | 2140 | 20,700 | 5,550 |

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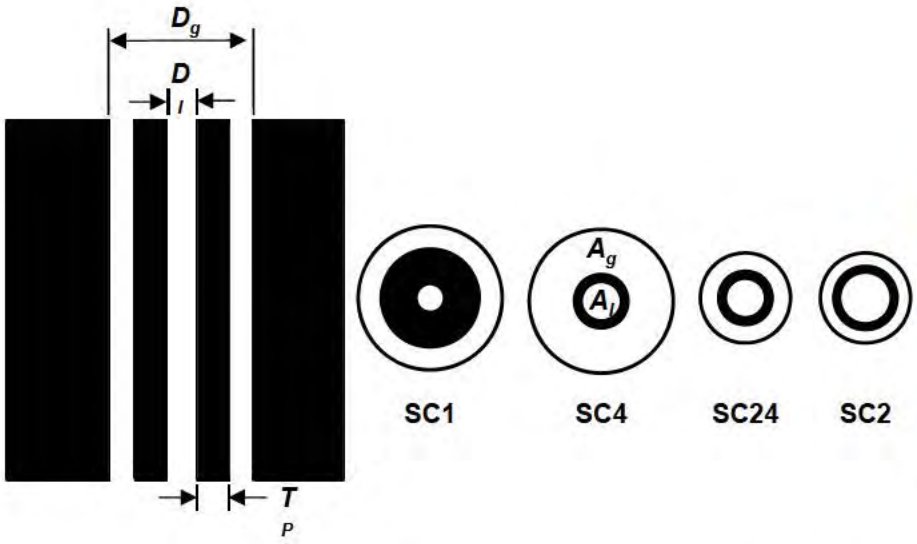
# Injector Geometries

- **Four injector geometries were used**
  - SC4 & SC24 have the same inner jet geometry ($D_I$ & $T_p$) but different area ratios
  - SC1 has a similar area ratio to SC4 but has a thickened injector post
- **Injector was tested in a horizontal configuration**
  - Injector face is sloped away from the jet




| Injector | $D_I$ (mm) | $D_g$ (mm) | $T_p$ (mm) | $L_i/D_I$ | $T_p/D_I$ | $A_g/A_I$ |
|---|---|---|---|---|---|---|
| SC1 | 2.08 | 10.2 | 2.32 | 48.8 | 1.12 | 13.4 |
| SC2 | 3.61 | 6.35 | 0.432 | 28.2 | 0.120 | 1.56 |
| SC4 | 2.79 | 10.2 | 0.457 | 36.4 | 0.164 | 11.5 |
| SC24 | 2.79 | 6.35 | 0.457 | 36.4 | 0.164 | 3.40 |

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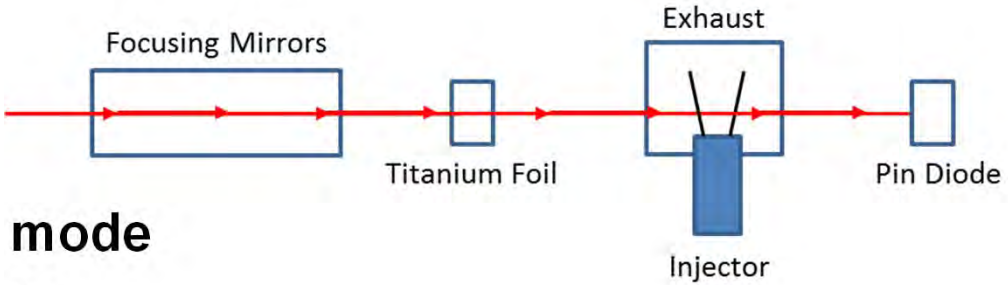
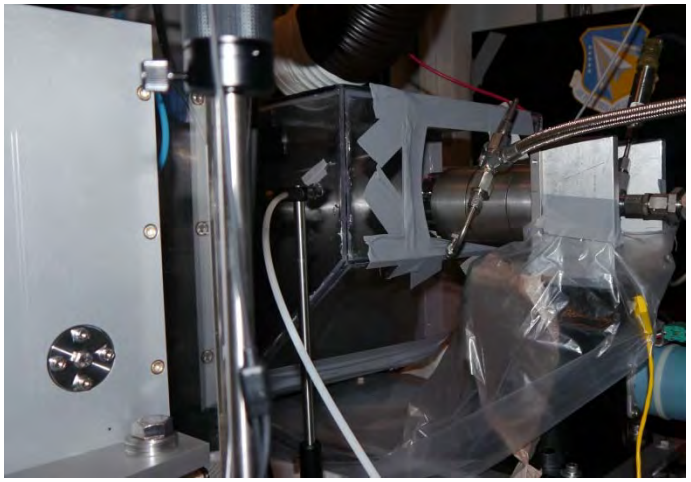
# Experimental Method

- **Measurements conducted at 7BM of the Advanced Photon Source**
  - **Beam size 7 x 8 μm FWHM**
    - Beam Photon Energy: 10keV
    - ΔE/E=1.4%
  - **Focused beam in raster-scan mode**
    - 1D transverse scans at 8 location
    - Scans perpendicular to injector axis
    - Scans collinear to injector axis
  - **Each point averaged for 5 seconds**
  - **Time resolved data (6 MHz) taken simultaneously**
    - Used for RMS calculations
  - **Beer's law used to convert x-ray transmission to mass/area in beam**
  - **Demineralized water absorption coefficient at 10keV: 5.33 $cm^2/g$**




Near Injector Optic Layout



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# Mobile Flow Laboratory

- **Self contained mobile system capable of delivering up to one kg/s of $H_2O$ & $GN_2$ at pressures in excess of 200 atmospheres**
  - Requires only power, $LN_2$, and exhaust from host facility
  - System fully rated to 408 atm (Allows more $GN_2$ storage)
  - Dedicated Allen-Bradley control & Pacific Instruments data acquisition systems
  - Remote operation
  - High speed abort system on all data channels for added pressure safety
  - System is on wheels and can be assembled in under 2 days
  - Ran almost continuously (20 hours/day) for two weeks

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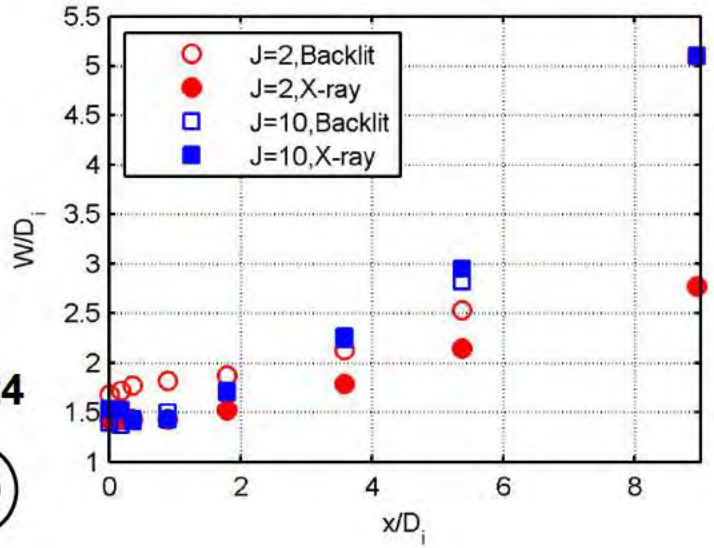
# Spray Width

- **Spray spreading is of primary interest in rocket engines and other applications**
  - Spreading provides some indication of mixing and of interaction between several injectors in an engine
- **Spray widths measured from shadowgraphy and X-ray radiography were compared**
  - The width data from both shadowgraphy and X-ray radiography were found to vary nonlinearly both very near the exit and farther downstream
  - Results show a lack of consistency between the widths measured via shadowgraphy and x-ray radiography
  - Results are not measuring spray width in the same way
  - Similar qualitative behavior shows that while the two methods are different, the results are complementary

SC24

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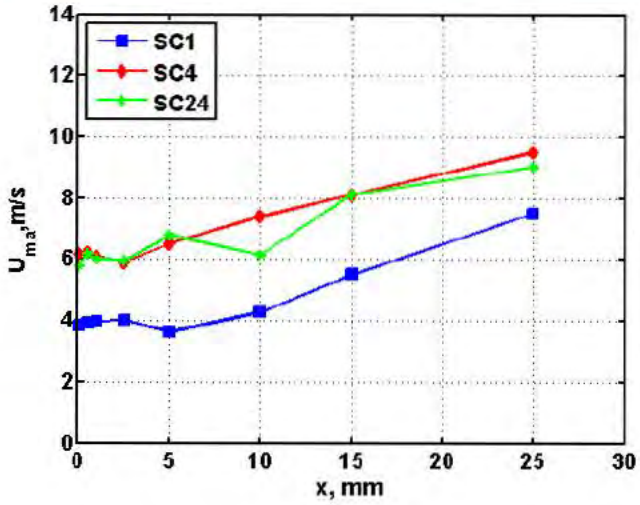
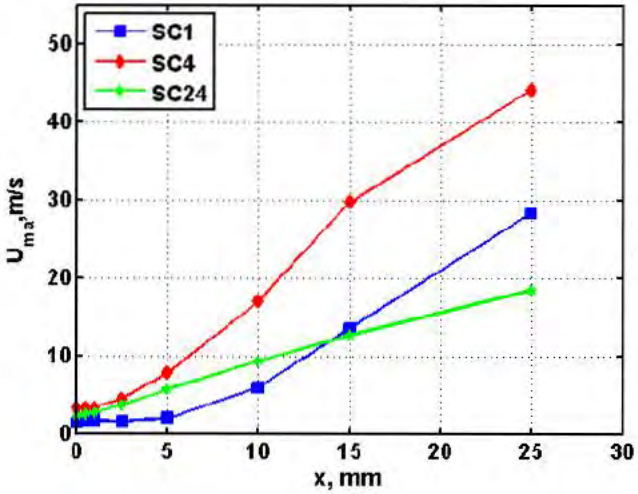
# Mass Averaged Velocity

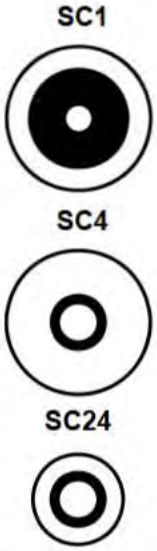
- **Obtained by dividing liquid mass flow rate by the integral of the radial liquid projected density profile**
- ***m* has a significant effect on the velocity in the far field**
  - Comparing SC4 (*m*=0.84) and SC24 (*m*=2.83) for *J*=10; increase in *m* is sufficient to decrease $U_{ma}$ from 23 m/s to 45 m/s
- **Liquid mass in the recirculation zones of SC1 results in $U_{ma}$ values below exit velocity**



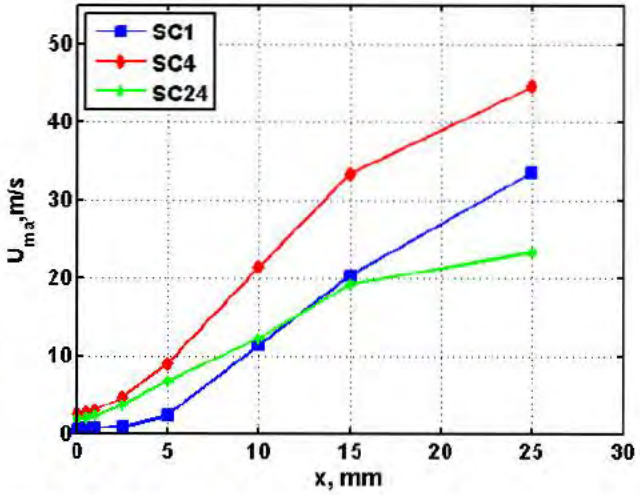

*J*=0.5




*J* =5.0




*J* =10

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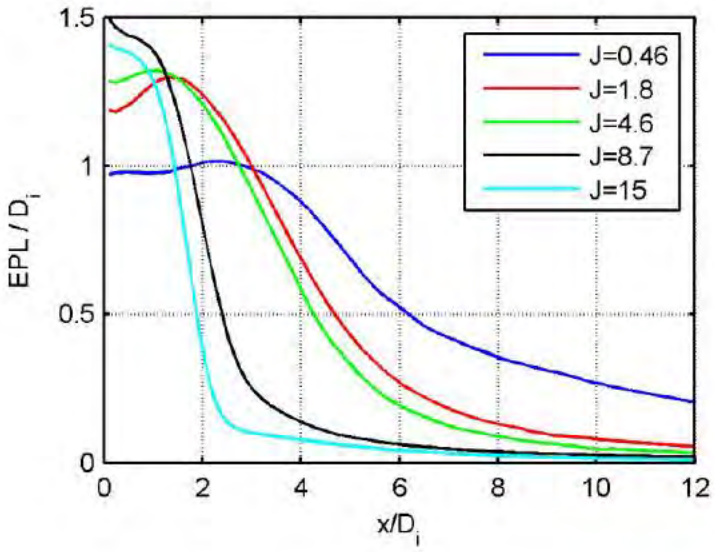
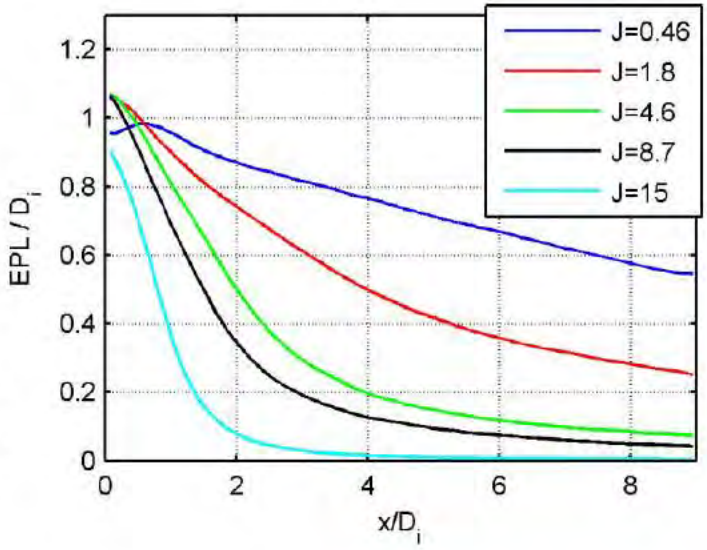
# Centerline EPL Profiles

- **Centerline EPL profiles shows same general trend reported in studies of the dark core length**
  - Increasing *J* accelerates primary atomization, thus shorting the liquid core
  - The shorting of the primary atomization region is observable from the decrease in the initial slope of the centerline EPL profiles
- **Normalized centerline profiles show expansion and contraction of the liquid core at injector exit for low *J* values (0.49 & 2)**



SC1

SC4

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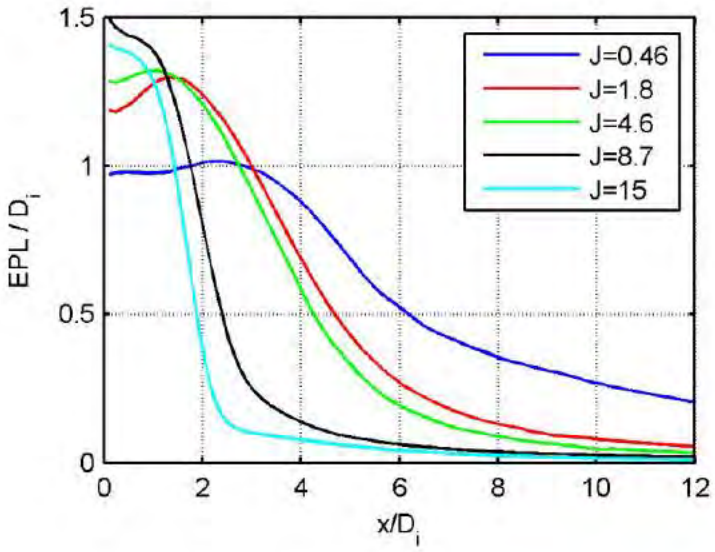
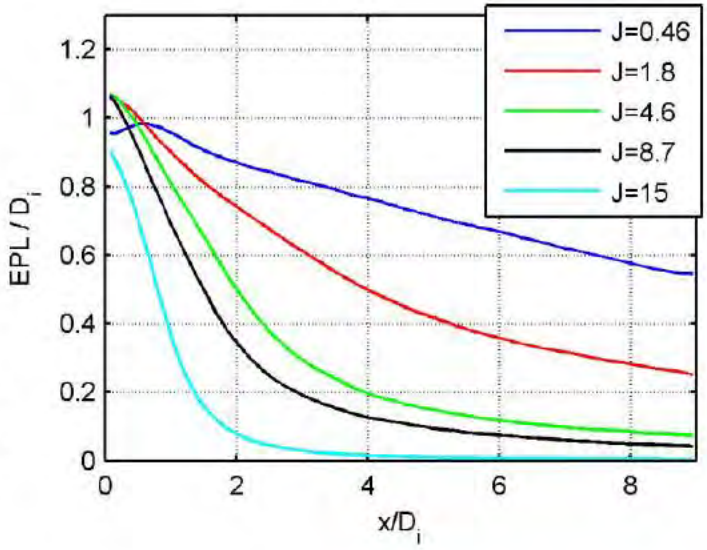


SC1

SC4

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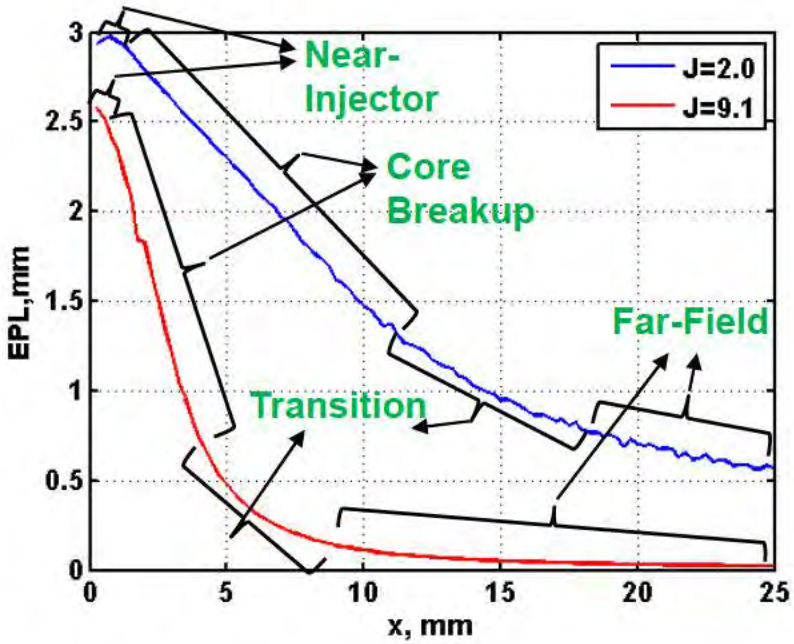
# Atomization Regions

- **Centerline EPL profiles can be used to identify four hypothetical spray regions**
  - **Near-Injector Region:** Characterized by either a constant or slight increase in the centerline EPL following the injector exit
  - **Primary Atomization / Core Breakup Region:** Characterized by a nearly linear decline in EPL
  - **Transition Region:** Characterized by a clear change in slope in the centerline Profiles
  - **Far-Field Region**: Characterized by a continuing drop in EPL as the spray widens and droplet velocity continues to slowing increase
- **What is the best method to measure core length from Centerline EPL profile?**
- **How do these core length measurements compare to backlit core lengths?**

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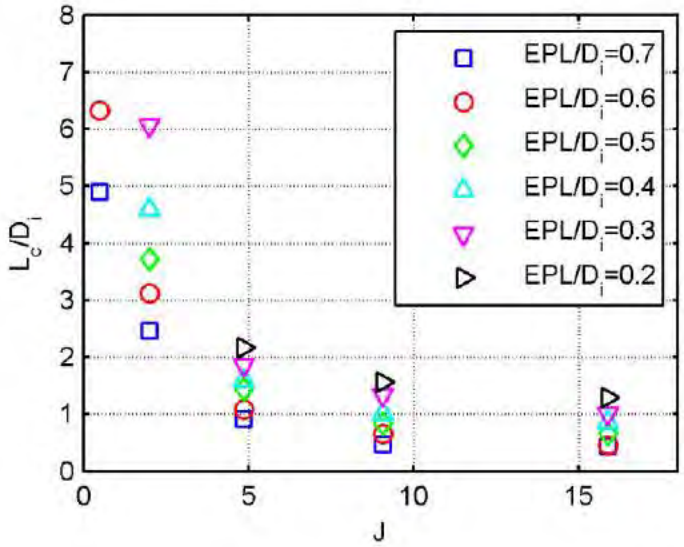
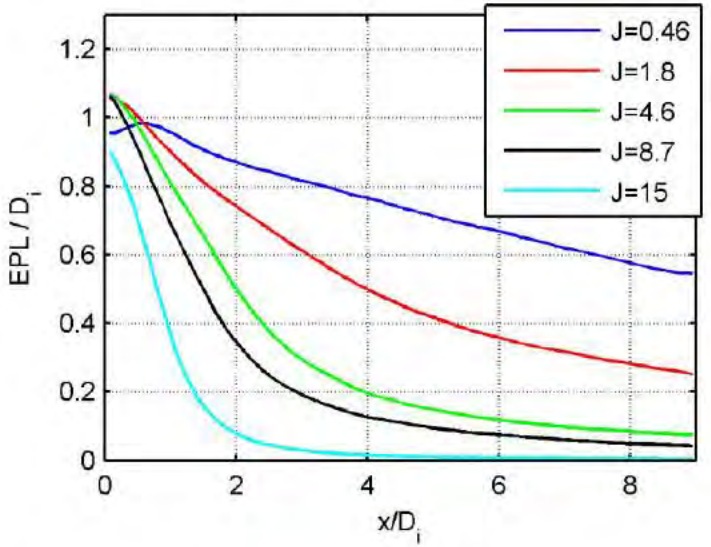
# Core Length Definitions

- **Three methods explored to measure core length from EPL data**
  - Percent decrease in EPL
  - Change in slope by calculating 1st spatial derivative
  - Peak EPL RMS
- **Percent Decrease in EPL**
  - After normalization it can be uniformly applied to all conditions and geometries
  - Theory does not provide a meaningful percent decrease



SC4

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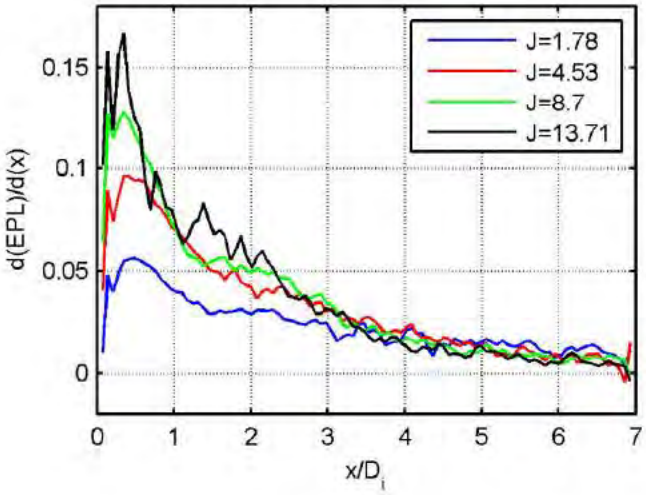
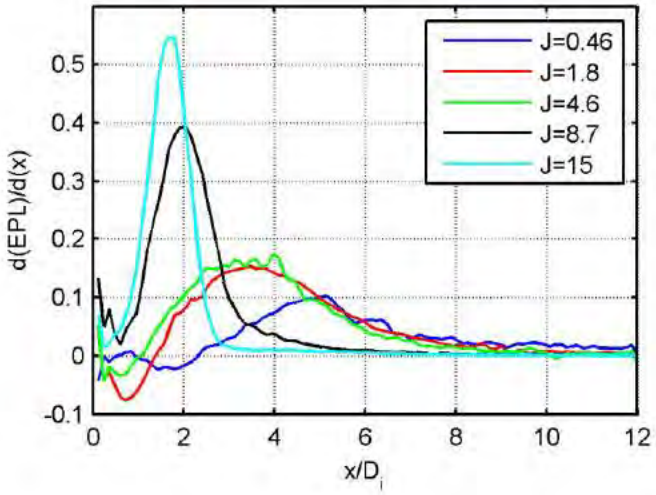
# Core length: Spatial Derivative

- **Spatial derivative used to capture change in slope at end of transition region**
  - Can be sensitive and noisy when applied to experimental data
  - Data was smoothed prior to taking the derivative
  - Unable to capture end of the core but was able to capture the start of the far-field

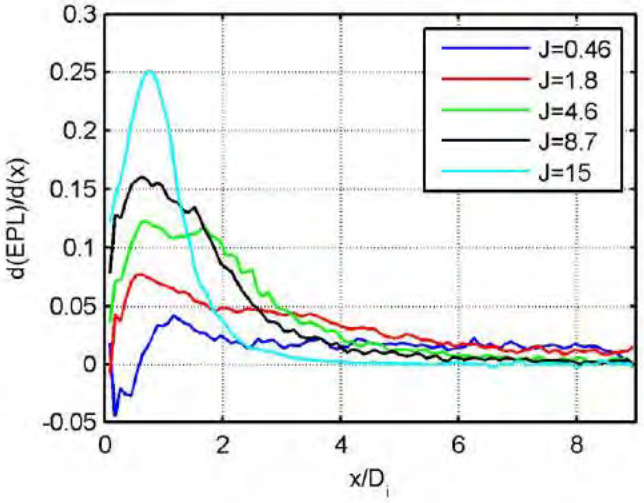
**SC2**




**SC1**




**SC24**

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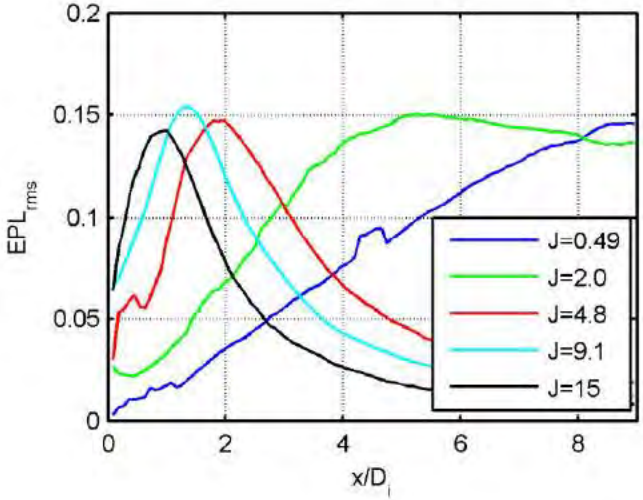
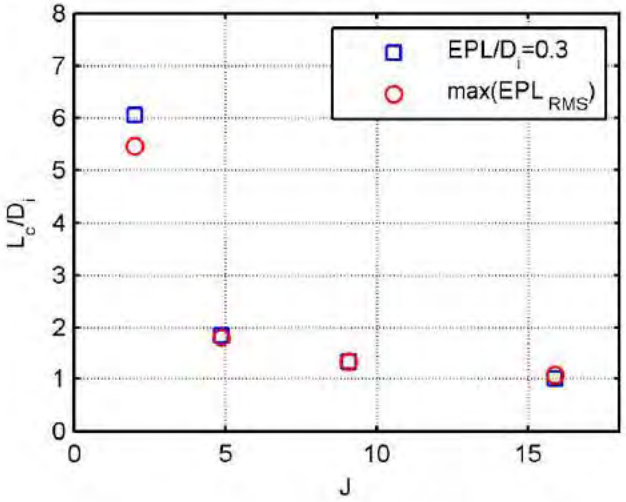
# Core length: Peak EPL RMS

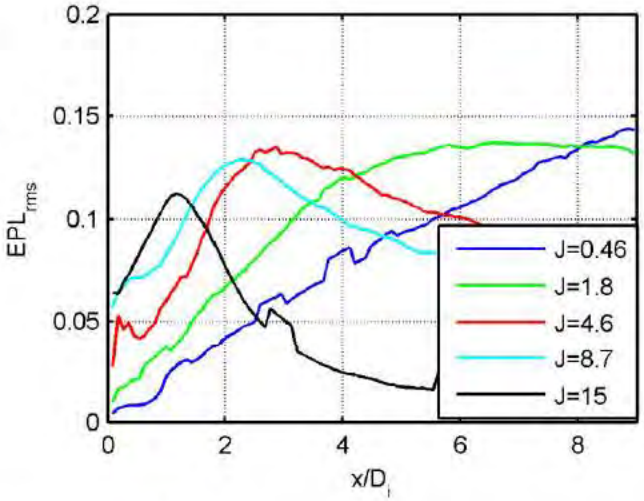
- **Peak EPL RMS as marker for core tip**
  - Due to dependence on mass flux and velocity dynamic slow moving liquid structures with high mass flux
  - On centerline it is hypothesized that the peak RMS corresponds with core tip
- **Peak RMS core lengths found to agree well with *EPL/D$_i$=0.3* core lengths**

**SC4**




**SC24**

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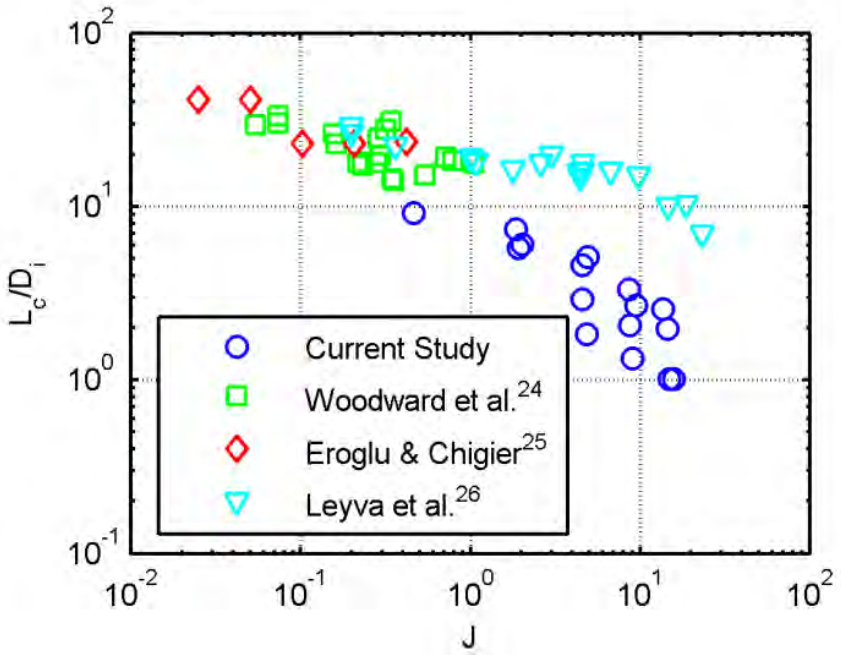
# Core Length Comparison

- **Current core length data (*EPL/$D_i$=0.3*) was compared to three two-phase shear coaxial data sets from the literature**
  - Woodward et. al. (1994): $N_2$ & $H_20$, Laboratory source X-ray radiography with a time-averaged thresholding method
  - Eroglu et. al. (1991): Air & $H_20$, Backlit imaging with an instantaneous thresholding method
  - Leyva et. al. (2007): $GN_2$ & $LN_2$, Backlit imaging with an instantaneous thresholding method

- **Fit from Leyva et. al.**
  - Between $18J^{-0.2}$ & $26J^{-0.2}$
- **Fit from Current Data**
  - $9.9J^{-0.66}$

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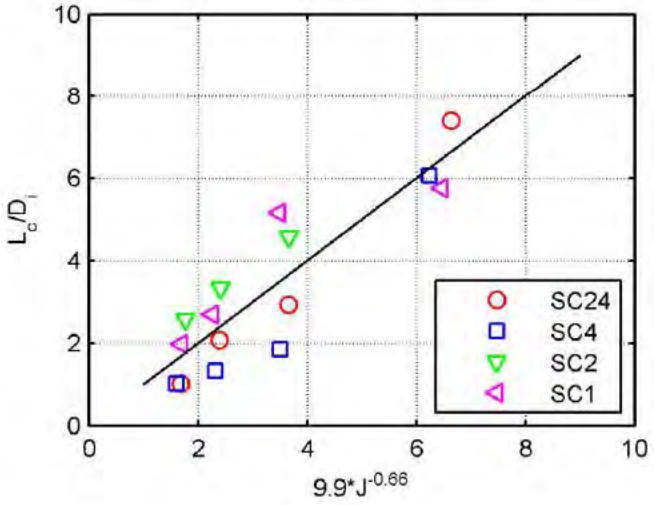
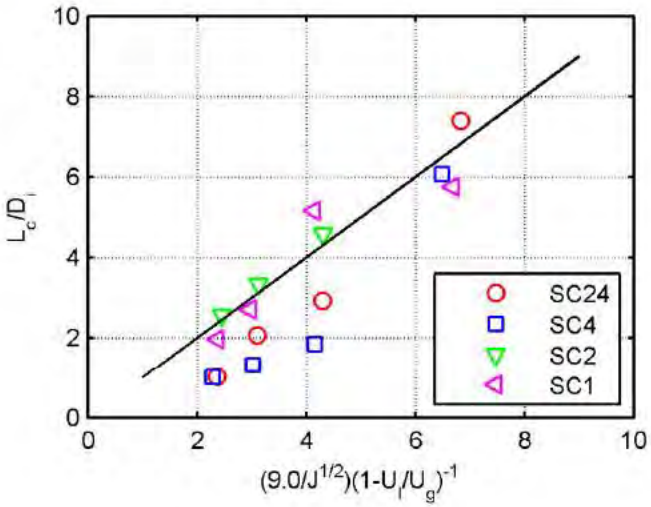
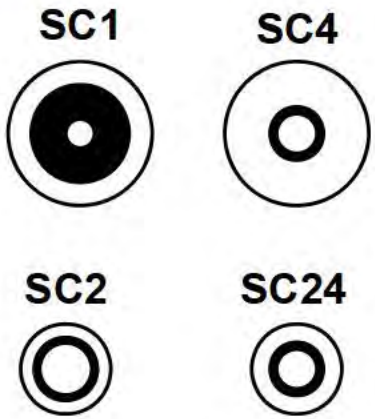
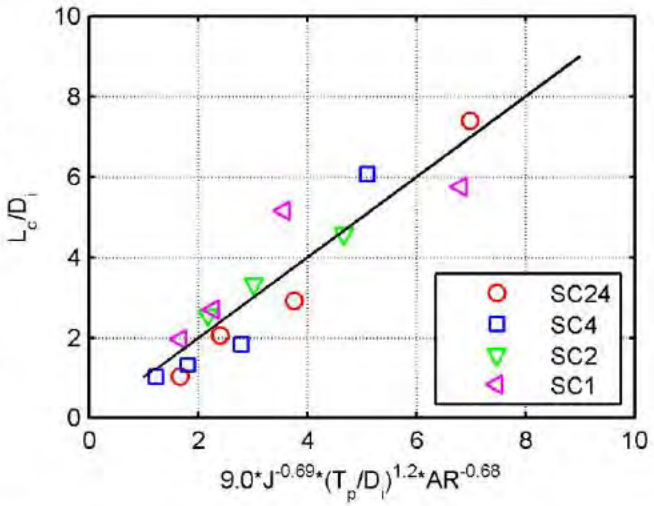
# Scaling

- **Three core length scaling laws were investigated**
  - Standard momentum flux ratio
  - Momentum flux ratio with area and tip post ratio
  - Momentum flux ratio with velocity ratio
- **Linear regression used to fit constants and exponents for the momentum and momentum flux ratio with area and tip post ratio**

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# Summary & Conclusions

- **X-ray radiography was used to obtain quantitative EPL profiles in shear coaxial rocket injectors**
  - 4 injector geometries and 5 momentum flux ratio values were studied
- **All test conditions were shown to be in the fiber-type atomization regime**
- **Centerline profiles were used to develop four hypothetical atomization regions**
  - Near-Injector, Core Breakup, Transition, and Far-Field
- **Three methods were investigated to define core length**
  - Percent decrease, spatial derivative, and peak EPL RMS
- **Core lengths obtained using a 30% decrease in EPL and the peak EPL RMS were found to have excellent agreement**
- **Core length data was found to scale with $J^{-0.66}$ which differs from the $J^{-0.2}$ suggested by other two-phase shear coaxial jet investigations**
  - Difference in scaling likely do to differences in measurement technique
- **In the future backlit images of the current test conditions will be obtained so direct core length comparisons can be made**
- **Additional work is needed to further understand how the X-ray radiography technique compares with prior investigations**

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# Backup: Important Parameters

- ***EPL*** Equivalent Path Length, pathlength-integral of liquid in beam
- ***m*** Mass Flux Ratio, $\rho_l U_l A_l / \rho_g U_g A_g$
- ***Oh*** Ohnesorge Number, $\mu_l / (\rho_l \sigma_l D_l)^{1/2}$
- ***Re$_g$*** Gas Reynolds Number, $U_g \left(D_g - (D_l + 2T_P)\right) / \upsilon_g$
- ***Re$_l$*** Liquid Reynolds Number, $U_l D_l / \upsilon_l$
- ***We*** Weber Number, $\rho_g {U_g}^2 D_l / \sigma_l$
- ***Φ*** Momentum Flux Ratio, $\rho_g {U_g}^2 / \rho_l {U_l}^2$

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